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Integrity assessment under various conditions of embedded fiber optics based multi-sensing materials

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ABSTRACT

The paper discusses new self-measurement and reacting materials with embedded sensors and actuators. New mechanical structures are made with a new integrated material that can almost inherently sense external effects e.g. temperature and deformation and react to them. Hence, the need to embed fiber Bragg grating (FBG) sensors that are inscribed in fiber optics inside materials for various applications e.g. structural health monitoring. The embedding technique can be part of the manufacturing process that can affect these delicate sensors. During this process, the sensors are subject to pressure, heat and deformation. The integrity of the sensors and the host material prior and after to embedding becomes very important. The paper discusses various characterization tests including strains, temperature, pressure and geometry effect on sensors placement while embedding within the host material subsurface. The results have shown that specific conditions are to be considered during the process of embedding to secure the integrity and good level of sensitivity of the sensors to deliver true measurements. The practice of these conditions has led to successful products.

1. Introduction

Innovative materials with embedded devices to sense, measure and react to external effects are requested to contribute in intelligent systems at small and large scale. The sensors while embedded inside the host material should be able to capture any phenomenon based on the sensor type, to measure it, and, to transmit the information. Several applications exist with coated fiber Bragg grating (FBG) e.g. hydrophones for underwater acoustic detection [1] and dynamic vertical force monitoring for elderly [2]. Other applications using fiber optics embedded inside materials e.g. monitoring liquid level with embedded fiber in silicone [3] and multi-parameter strain sensing with sinusoidal embedment in composite materials [4,5]. Other targeted products include sensorial materials and nervous materials with combined embedded sensors and actuators as discussed in [6].

When the fiber optics are embedded inside materials e.g. plastic or metallic, the integrity has to be verified. Conditions of non-violation of integrity are on two levels; the sensors integrity when embedded in the host material, and the material integrity at the interface between the sensors and the host material. The paper discusses the first level of integrity if FBG sensors for multiple measurements are used.

The deployment of FBG sensors for large and complex mechanical structures can be challenging through embedding at the materials subsurface or even inside the materials. This process is host material dependent. The materials can be composite, plastic or metals is extensively discussed in [7,8]. The embedding manufacturing processes can also vary depending on the material [8] e.g. manual setting, gluing, and ultrasonic consolidation in plastic or metallic materials [9] (Fig. 2b), powder based material with compaction followed by sintering, and rapid prototyping with laser sintering or 3D printing using polymer materials e.g. ABS, PLA (Fig. 2a). The latter method has been considered in this paper.

In this case, fiber embedding is performed while the material printing is in progress. In general, the host material and the overall structure can have critical areas where the sensors and actuators need to be embedded in order to monitor structural behavior and react to it as shown in Fig. 1-a. The FBG sensors embedded in various locations require a distribution of FBGs with the fiber to bend according to sensors placement along the fiber. In the process of embedding, the fibers can be subjected to high temperature, pressure, deformation and strains as shown in Fig. 1-b where any action on the part is followed on the laptop screen by an instant computation of the deformation, for example, through the capture of data from the embedded sensors to the computer. Immediate

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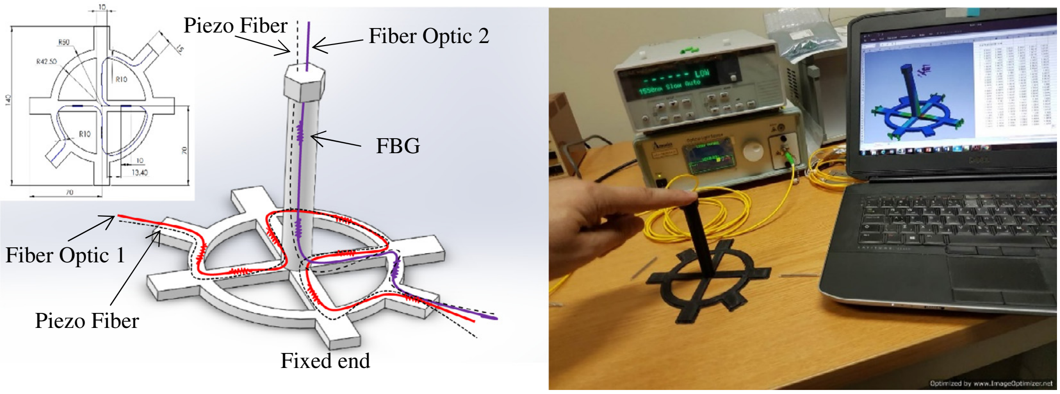

Fig. 1. Real part made with ABS in 3D printing hosting FBGs distribution in live deformation.

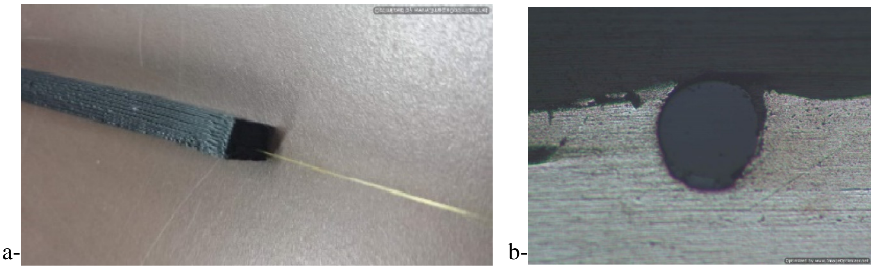

Fig. 2. a) Fiber optic embedded in ABS printed material. b) Cross section of fiber embedded in aluminum.

reaction from the piezo fibers is then expected to resist large bending.

The single mode fiber is embedded without its jacket inside the material. It is composed of a silica core with a cladding and an extra coating totaling an average diameter of 270 μm (Fig. 3). It can be re-coated and it is subject to tension and pressure caused by the embedding processes as the fiber is in direct contact with the material at elevated temperatures in all mentioned processes. Since the fiber is manually placed inside the material with various geometries i.e. linear, circular with tight corners, it was logical to check aspects of integrity of the sensors to guarantee its use. Hence, with the increased complexity in verifying the performance of these materials, the characterization of the fibers becomes important. Fiber characterization is defined as a series of tests performed on optical fiber span to verify its integrity after being subject to geometry, load and temperature variations. It is worth noticing that the interrogator supplies fiber optics with low level power light e.g. average of 0.18 mW and hence with multiples FBGs in a serial configuration, a question arises whether the last FBG would still be able receive enough power to measure, hence whether there is there any power limitation over distributed FBG series.

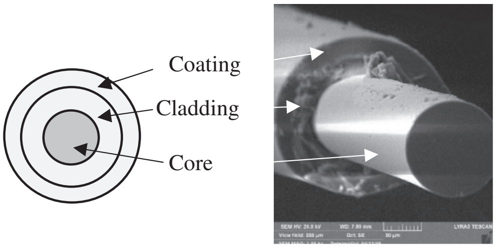

Fig. 3. Optical fiber schematic and its SEM picture.

New design and embedding applications require characterization customized to the needs of the customer or end user. Sensor calibration and characterization is an important step in developing new systems. For example, usage of optical fibers is gaining tremendous attention in the field of aerospace, oil and gas and biomedical sector [6–8]. The novelty of design and application inspires us to use existing material characterization with customized test setups and investigation methods. Works like [7,9–11] are examples of implementing fiber characterization techniques to suit applications without hindering system performance and retaining sensor integrity. The sensor response to different measurands like force, pressure, temperature and strains show the effectiveness of an FBG sensor in particular loading scenario. The aim was to build innovative products [12] based on nervous material having embedded fiber optic and piezoelectric actuators that can be of low power [13]. The following sections provide details for various characterization methods for fiber optic sensors under several constraints in term of force, temperature, pressure and various geometric constraints. The objective was to develop guidance to embed fiber optics inside materials in different shapes and to secure their proper functioning after being embedded.

2. Characterization of fiber optics

Any embedded fiber optic with several FBGs inside a material is subject to external effects such as pulling, compressing, pressure and temperature. The following tests will characterize the fiber in various aspects previously introduced and show limitations.

We have considered a fiber optic embedded inside ABS material using 3D printing where the temperature can reach 230 °C. The obtained host material samples have several sizes i.e. $10 \times 10 \times 100$ mm and $10 \times 30 \times 1000$ mm. The embedding process is carried out while the printer is building the host material. The pose of the fiber optic is done when the building reaches half-